Fire Research Note

No. 624

A NOTE ON THE OCCURRENCE OF FIRE AND EXPLOSIONS IN SPIRIT WAREHOUSES

by

D. J. RASBASH

FIRE
RESEARCH
STATION

F.R. Note No. 624
May, 1966.

A NOTE ON THE OCCURRENCE OF FIRE AND EXPLOSIONS IN SPIRIT WAREHOUSES

by

D. J. Rasbash

SUMMARY

The experience of fire occurrence and loss in spirit warehouses has been examined. Particular attention has been paid to causes of ignition, fatalities, the occurrence of building collapse and the spread of fire by exposure.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

F.R. Note No. 624
May, 1966.

A NOTE ON THE OCCURRENCE OF FIRE AND EXPLOSIONS IN SPIRIT WAREHOUSES

by

D. J. Rasbash

Introduction

A Code of Practice on Fire Precautions in Spirit Storage Premises such as bonded warehouses is currently being prepared for the Joint Fire Prevention Committee of the Central Fire Brigades Advisory Councils for England and Wales and for Scotland. As part of the background in the preparation of this Code, experience of previous fires and explosions in bonded warehouses has been examined. This experience is summarized in this note.

Occurrence of fires

A source of information on the occurrence of fires in spirit storage in the United Kingdom is the United Kingdom Statistics on fires attended by the Fire Brigade. Although reports are returned for every fire attended by the brigade, because of shortage of staff, it has been possible in only a few years to code all the reports received from this source and in most years only a fraction of reports received have been coded. The number of fires in spirit warehouses which were found in that fraction of the fires which had been coded is shown in Table 1.

Table 1

Numbers of fires in warehouses for wines and spirits

Year	Reciprocal of fraction of fires coded	Number of fires in coded sample
1948	1	3
1949	4	0
1950	2	0
1951	2	0
1952	4	0
1953	5	1
1954	2	0
1955	4	0
1956	4	0
1957	1	0
1958	4	1
1960	4	0
1962	2	1
1964	2	2

In six of the incidents listed in Table 1 the causes of the fire were as follows:-

Two were due to a heating appliance in the roof space;
Two were due to a lighted cigarette end;
One the heat from a toilet incinerator;
One was due to a quantity of waste paper in a waste paper bag ignited by an unknown agent.

None of the fires listed in Table 1 became large.

It is clear that although Table 1 does not provide a precise estimate of the number of fires attended in spirit warehouses, these fires are very rare and occur approximately at the rate of about one to two a year. Further evidence of the comparative rarity of fires in these warehouses may be obtained from an analysis carried out recently on the relative fire hazards of different industries (1). In this work a comparison was made between the tendencies for fires to occur in the storage areas of different industries, due allowance being made for the different sizes of the industries by the use of statistical techniques. The tendency for fire to occur averaged from a minimum of 0 for the metalworking machine tools' industry to 78 for the wooden containers and basket industry. On this scale the figure of three was obtained for the storage areas associated with spirit distilling and compounding. The numbers may be approximately interpreted as the number of fires that would occur in the particular industry in four years if the industry concerned was one of average size.

Occurrence of large fires

Large fire experience in spirit storage, both in this country and the United States may be obtained from a dossier by Richard M. Patton (2) on fire loss experience and fire protection data for the distilling industry. The information in this section is taken from this compilation supplemented by special reports at the Fire Research Station.

Financial loss

Patton lists 15 fires occurring in whisky warehouses as having taken place between 1935 and 1963. The financial damage caused by these fires has been analysed in Table 2.

Table 2

Financial damages in whisky warehouse fires (after Patton)

	Sprinklered premises		Non-sprinklered premises		Total
	U.S.A.	U.K.	U.S.A.	U.K.	
Total number of fires	3*	0	7	5	15
Loss $56,000 - $280,000	0	0	0	1	1
Loss $280,000 - $1,000,000	0	0	3	1	4
Loss greater than $1,000,000	1	0	4	2	7

*In one of these fires the loss was less than $56,000 and in another the sprinklers did not operate because the fire was too small.

In the United Kingdom a fire with a loss greater than £20,000 is regarded as a large fire and greater than £100,000 as a very large fire. According to this classification 12 of the 15 fires listed were large fires and 11 were very large fires. Four of the large fires were stated to have occurred in the United Kingdom as follows:-

(1) South Queensferry 1949, ($1,400,000)
(2) Quality Street, Leith, 1955, ($900,000)
(3) Arbuckle Smith and Co. Ltd., 1960, ($8,400,000)
(4) 10/12 and 26 Oswald Street, Glasgow, 1963, ($79,800).

The statistics on numbers of fires attended by the Brigade indicated in the previous section suggest that the total number of incidents listed by Patton as taking place in this country is probably an underestimate. However, the above list includes all the major fires that have taken place in the United Kingdom since 1948.

The cause of 9 of the 15 fires listed by Patton is unknown. Two were caused by lightning (Pekin, Illinois, 1954, and Renlea Distillery, Kentucky, 1960). One was caused by sparks from an unattended chimney fire which ignited roof timbers, and one was caused when gasolene was used to ignite a fire near the warehouse. In one of the three small incidents listed a portable steel barrel collapsed which produced a spark that ignited a small fire which was extinguished by buckets of water, and in another a dump trough overflowed on to a light fixture. In the latter incident the fire was controlled by sprinklers, the indicated fire loss being $7,700.

Collapse of buildings

In three of the 15 incidents listed by Patton there was a sudden major collapse of the building which according to the available evidence were probably the result of a vapour flashover or explosion. The three incidents were:-

(1) Hiram Walker & Sons Inc., Peoria, Illinois, 1935. (Sprinklered building loss $1,850,000);

(2) American Distilling Co., Pekin, Illinois, 1954. (Non-sprinklered building loss $7,500,000);

(3) Arbuckle Smith & Co. Ltd., Glasgow, 1960. (Non-sprinklered building loss $8,400,000).

The history of the first of these incidents is not generally known and the following information has been abstracted from Patton's compilation:-

"For at least several weeks prior to the loss of this fully loaded warehouse it was known to be out of plumb and gradually shifting. Contractors had been called in to install the necessary reinforcing members. Plant management did not anticipate that there was imminent danger of collapse. Presumably, necessary corrective action was being taken to properly straighten the building and a careful check was maintained of the condition of the building at all times. With the building out of plumb, the elevator could not be operated to remove inventory.

"The afternoon of July 22 workmen were in the building and they noticed an unusual creaking of the timbers. Investigation disclosed the south wall bulging. Additional reinforcing was installed. The main controlling switch for electrical equipment within the building was pulled.

"At 10.13 p.m. that evening an automatically transmitted central station signal was transmitted from sprinkler systems within the building. This indicated water was flowing. At the same time as the transmission of the signal, or shortly after it, the warehouse collapsed and burned.

"The fire rapidly became a holocaust. The radiant energy ignited a nearby cooper shop and also the bottling building.

"The responding Fire Department turned in the second alarm as soon as they arrived at the plant. Soon five pumpers, four ladder trucks, and three hose trucks were at the scene. The 14 broken sprinkler risers in collapsed Warehouse No. 3 permitted large quantities of water to flow thus dropping pressure in the mains in the vicinity. This drop in pressure was noticeable to sprinklers in the cooper shop and the bottling house. They were not effective in controlling the fire. However, soon after the Fire Department arrived sectional control valves were closed stopping the water flow through the broken risers and hose lines were used to extinguish fires in the Bottling Building and cooper shop. Fire Department operations went on through the evening into the morning hours. By 3.00 a.m. the fire was definitely confined to Warehouse No. 3. The 16 hose lines in use up to this time were cut back to 8. The 8 lines were kept in operation, wetting down the burning debris, for another 36 hours.

"Rack Warehouse No. 4, which was to be of the same size and shape as Warehouse No. 3, was in the course of construction 50 feet removed. This partially constructed building was wet down by hose streams during the height of the fire and it did not become involved.

"This occurrence raised the question as to whether the fire occurred before or after the collapse. Two impartial witnesses (they were not employed by Hiram Walker) who observed the collapse from a distance reported they first saw a flash, then the collapse of the building. Assuming this is an accurate account, it is possible that one or more barrels of whisky rolled loose from the racks and vapors from the escaping liquid formed an explosive mixture with the air. The presumed explosion which developed was too much for the already weakened warehouse and it collapsed. This is one theory but no one knows with certainty exactly what did happen."

An account of the second incident has been given in the National Fire Protection Association Quarterly, January, 1955 (3). This account describes that the fire built up over a period of several hours in the warehouse concerned after another fire had burned out two spirit warehouses nearby and that the firemen had great difficulty in fighting the fire because of the heat and the smoke-logging. Immediately before the explosion the roof became very hot. The explosion, which was violent, was stated to tear the building apart. This is consistent with an explosion involving a large volume of a hot vapour/air mixture. The premises were unsprinklered, but there was little doubt that if sprinklers had been present they would have operated and probably brought the fire under control long before the explosion occurred.

The third explosion, of course, is well known and indeed was the main reason for setting up the Committee for drafting regulations for spirit warehouses. The evidence that the collapse was caused by a vapour explosion was:-

(1) The collapse occurred in two end walls simultaneously. It is most unlikely that this would have happened if there had been a structural collapse as a result only of a movement of the wall supports.

(2) The collapse was immediately preceded by a "whoosh", which is a characteristic noise for a weak vapour explosion.

(3) The above noise was also immediately preceded by the appearance of a small flame.

However, there is little doubt also that the vapour explosion which caused the collapse must have been a very mild one. The evidence for this is that the two walls which were not blown out were not damaged. Although there was smoke-logging associated with this fire the firemen reconnoitring the fire did not find any evidence of heat development. For this reason one cannot be certain that if sprinklers had been installed they would have operated prior to the explosion.

An account of some of the possible ways in which a vapour explosion might occur during the course of a fire is given in the Appendix.

In addition to the three incidents itemized above in which there was a collapse of a warehouse, probably as a result of a vapour explosion, there were also two incidents during which three warehouses collapsed in an unspecified manner. The first of these was at the Kentucky River Distillery, October, 1949, where the warehouse was described as having collapsed about one hour and twenty minutes after the fire was discovered, but no information is provided, however, on the circumstances of this collapse. The other two also occurred at the incident at Pekin, Illinois, in 1954, at which the warehouse which was originally struck by lightning and a neighbouring warehouse 50 ft away to which the fire spread, both collapsed after about one hour. The major violent explosion at this incident referred to earlier occurred in a third warehouse about 18 hours later. Patton makes the point that this latter building exploded violently because it was windowless, but that the warehouses which collapsed had windows and as a result they "burned".

It is interesting, however, to compare this experience with that of the two bonds that were destroyed at the Queensferry fire (Scotland, 1949). When the Chief Fire Officer arrived the roof of the bond on the first floor had completely collapsed with the bond completely involved in fire, and smoke was issuing from the roof of the second bond. This latter building was a three-storey building with wooden floors and contained a number of windows. During the development of the fire in the second bond a "Blow-out from the built-up spirit vapours" occurred several times through these windows in a manner similar to a "Flame-thrower of 5 to 10 seconds' duration". There is no mention of collapse of this building in the accounts of this fire and photographs taken after the fire showed that a large part of the shell of the building remained standing. From these photographs it was also estimated that windows occupied about 20 per cent of the wall area of this particular bond.

Casualties

Patton also lists fatalities and injuries that occurred in the fires in the United States, and combining his figures with figures for the incidents he lists for this country obtained from the United Kingdom Fire Statistics, shows that in the 12 large fires there were 26 fatalities and 33 injuries. Twenty-five of the fatalities and 28 of the injuries occurred during the Pekin, Illinois and the Arbuckle Smith, Glasgow, fires and were a direct result of the sudden unexpected collapse of the building. The remaining fatality was due to an explosion in gasolene which was the cause of one of the fires, when the person killed used gasolene to light a fire in a yard nearby. It is noteworthy that in four instances warehouses have collapsed without causing fatalities. In one of these cases (Peoria, Illinois, 1935) there was nobody in the immediate vicinity, but in three cases firefighters were present. This suggests that in these latter three cases the collapse when it occurred was not entirely unexpected.

Exposure risks

In four large fires there was a hazard due to flowing spirit that was burning. Usually firefighters were successful in dyking or trenching the flowing spirit, but in one incident there are reports of small buildings becoming ignited, up to 160 ft away from the fire. It is noteworthy that in two instances in which a building collapsed little spirit flowed out of the buildings because of a reservoir formed below ground level between the building walls.

In six of the incidents there were reports of buildings at a distance becoming ignited by the exposure to the original fire. In one case a warehouse at a distance of 149 ft was reported as being ignited at eight points simultaneously. In another case windows in buildings were reported as being scorched 260 ft away from the fire, but it is not clear whether this was due to the presence of burning spirit that may have been flowing nearby.

In three incidents fire spread from the warehouse in which the fire started to at least one other warehouse which was also completely destroyed. Six further warehouses were destroyed in this way, three of these occurring in one incident. In five of the six incidents the fire spread by radiation exposure, the exposure distance being in all cases about 50 ft. In one instance the fire probably spread through fire doors that had been left open (Queensferry, 1949). In all these incidents there was a delayed call to the public brigade and/or an inadequacy of fire cover by the public authorities. In two incidents where there was good local fire cover (Leith, 1955, Arbuckle Smith, Glasgow, 1960) only minor fire damage was caused to neighbouring buildings ignited by exposure even though these were less than 50 ft from the original fire.

Discussion

In spite of the smallness of the number of incidents available it is possible to reach some firm conclusions concerning the nature of the fire risk associated with spirit storage. Firstly, fires are rare. This is probably due to the strict security precautions observed for these warehouses. Secondly, a high proportion of the fires that occur become very large. Thus, on the assumption that there has been about 25 attendances at whisky storage premises in the United Kingdom in the last 15 years, then in four of these fires the loss exceeded £20,000 and in the three the loss exceeded £100,000. This may be compared with a general expectation for industrial fires of about 1 in 25 exceeding £20,000 and 1 in 100 exceeding £100,000.

Thirdly, during the course of large fires in spirit bonds there is also an abnormally high chance of a sudden major collapse of the walls or even the whole building. This has occurred on at least six occasions out of a possible seventeen buildings. In three of the six there is evidence that the collapse was due to a vapour explosion. The occurrence of a sudden major collapse of the walls of a building in a large fire is very rare. Evidence for this was obtained by an examination of a random sample of one hundred five (or more) jet fires occurring in the United Kingdom in 1964. (A five jet fire is approximately the same order of size as a £20,000 damage fire). In none of these fires did a major sudden collapse of the walls take place. (In nine incidents there was partial collapse of the roof and walls due to the fire, in one incident the roof collapsed as a result of a "flashover" and the walls were made unsafe, and in another incident a floor collapsed and windows were blown out as a result of an explosion in town gas).

The tendency of the buildings to collapse in fires may be associated primarily with the volatile nature of the spirit and the very large quantity stored, combined with the restricted areas through which a rise in pressure may be relieved. As indicated in the Appendix very small fires may volatilise sufficient liquid vapour to cause on ignition the collapse of the building. Larger fires can vaporize sufficient alcohol to produce over-rich mixtures in the whole of a compartment. Even with a good supply of windows this vapour tends to burn in pulses at the windows, as indicated by the Queensferry fire. Pulses of this kind are usually associated with pressure effects which may bring about building collapse. Smoke explosions and "flashovers" are, of course, also known to occur in other fires. However, they rarely lead to collapse, partly because burned decomposition products of solid combustibles are more difficult to produce and give a less vigorous propagation of flame than alcohol vapour, and partly because the doors and windows present can usually be easily blown open by a pressure pulse.

Because of incidents in which there was a sudden unexpected collapse of walls the number of casualties that have occurred in large fires in spirit storage premises is very high. Thus, the examination of the hundred five jet fires mentioned above revealed that there were 15 injuries and one fatality associated with these fires. This may be compared with a total of 33 injuries and 26 fatalities that have occurred in 12 large fires in spirit storage premises.

There are only two cases on record in which installed sprinklers operated. In the first the fire was extinguished with a little loss. In the second the building collapsed and there was complete destruction of buildings and contents. With the possible exception of the Arbuckle Smith Warehouse, in all other warehouses where collapse occurred the fire reached a stage which should have operated sprinklers before collapse. It is very likely that these warehouses, in addition to those warehouses that were destroyed without collapse would have been saved by sprinklers or an alternative fire protection installation of efficiency equal to sprinklers.

There are many fires in spirit warehouses in which neighbouring buildings have been ignited by exposure. One building 149 ft distant from the fire was persistently ignited in this way. However, if the call is not delayed and the Fire Brigade cover is good, the experience shows that these fires can be brought under control even when the exposure distance is less than 50 ft. Rivulets of burning spirit are also a hazard, but this again does not appear to have been responsible for spreading fire seriously to other buildings which fireman have been in a position to protect.

References

(1) HOGG, J. M. and FRY, J. F. The relative fire hazard of different industries. F.R. Note No. 597. Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization, May, 1965.

(2) PATTON, R. M. Distilling Industry, Fire Loss Experience and Fire Protection Data. Joseph E. Seagram & Sons, Inc., 1964.

(3) National Fire Protection Association Quarterly, January, 1955. Whiskey. Vol. 48, No. 3, page 249-250.

(4) Principles of Modern Building. H.M.S.O. 1959, Vol. 1, page 166.

(5) BURGOYNE, J. H. and NEWITT, D. M. Trans. Inst. of Marine Engineers. 1955, 58 No. 8.

(6) Pressure developed by Rapid Combustion. Factory Mutual Laboratories. Report No. 12555-51. February 4, 1955.

APPENDIX

COLLAPSE OF BUILDINGS BY EXPLOSIONS

The most likely cause of an explosion sufficiently powerful to bring about the collapse of part or the whole of a building is the ignition of a pocket of gas containing alcohol vapour within the limits of flammability. There are several ways in which such a pocket of gas may be obtained and these are discussed below. Another possible cause is the rapid inflammation of a very large quantity of spirit spread over a large area. The vapour in this case need not necessarily be mixed with air and be within the limits, but air must be available for combustion to take place.

Ignition of a pocket of vapour and air mixture

Size of pocket required

It has been stated above that ignition of alcohol-air mixtures inside a confined space will bring about an increase in the internal pressure to between 50 and 100 lb/in^2 depending on the concentration of the vapour. Now unless a building is specially built to resist explosion it is very unlikely that it will survive an internal pressure of $\frac{1}{2}$ to 1 lb/in^2 (72 - 144 lb/ft^2). Thus storey height brick walls, $4\frac{1}{2}$ in, 9 in and $13\frac{1}{2}$ in thick, built in cement/lime mortar, when supported at top and bottom and subjected to lateral loading only, may fail under lateral pressures of about 10, 50 and 100 lb/ft^2 respectively [(4)]. A pressure of $\frac{1}{2}$ lb/in^2 (72 lb/ft^2) may be reached if a pocket of stoichiometric vapour air mixture 1/200th of the volume of the compartment explodes, or a pocket of the lower limit mixture 1/100th of the volume of the compartment explodes. Thus if a compartment has a volume of 300,000 cubic feet the ignition of a pocket of lower limit mixture 3,000 ft^3 in size or of stoichiometric mixture 1,500 ft^3 in size may produce a pressure sufficient to damage the building. The amount of alcohol that needs to be present in such pockets may be produced from about 2 gallons of 20 over proof spirit.

Methods of production of vapour air pockets

There are at least five ways in which a pocket of vapour air mixture may be obtained.

1. Evaporation of alcohol following a leak of spirit under otherwise normal conditions.

2. Evaporation of alcohol from a spillage into a hot atmosphere caused by a fire.

3. Evaporation of alcohol from a leak onto a hot surface caused by a fire.

4. Production of an explosive atmosphere inside a tank or cask.

5. Evaporation of alcohol into an oxygen deficient atmosphere, followed by the introduction of air.

1. A flammable atmosphere will not be produced by method 1 above unless the ambient temperature or the temperature of the surface on which the spillage occurs exceeds the flash point. For 20 o.p. spirit this is 70°F. At higher temperatures, if there is no ventilation, it is possible to fill the whole of a building with a flammable atmosphere if the leak continues. Nevertheless, a very moderate amount of ventilation will suffice to disperse the alcohol vapour before pockets of any appreciable size are formed.

2. The rate at which alcohol is evaporated from a spill increases considerably as the ambient temperature of the atmosphere increases. Tests carried out by the Underwriters' Laboratories indicate that spillage of 48 U.S. gallons will produce a spill area of 1,000 ft^2. It may be estimated that such a pool would vaporise at the rate of 0.07 lb/s when the ambient temperature is 135°F. The extent to which this evaporated solvent would form a pocket of flammable gas will depend upon the ventilation rate.

3. A fire, as well as heating the contents and atmosphere of a compartment, may also heat much more intensely surfaces of a limited area very near the fire. A leak of spirit on to the hot surfaces so produced may bring about a rapid evolution of vapour. As long as a flame is present, sufficiently close to the point of evolution of such vapour, the latter will inflame harmlessly before a sufficiently large pocket is produced. However, if there is no flame sufficiently close (a pocket of 1,500 cubic feet suggests that flame would need to be within about 6 feet) a dangerous pocket can be formed. This may then be ignited either by a sufficiently hot part of the surface or by a flame. No surface will ignite the vapour unless it exceeds a temperature of 800°F; with surfaces of higher temperature the ignition of the pocket will depend on a number of rather intractable factors e.g. the surface shape and size. This mechanism of producing a vapour pocket and its subsequent ignition is similar to the generally accepted mechanism whereby crankcase explosions are obtained in ships [(5)]; the only essential difference is that in crankcase explosions the hot surfaces are obtained by friction whereas in the present instance they are obtained by fire.

To evaporate 18 lb of spirit will require the transfer of about 9,000 Btu from the hot material to the spirit, this heat may be contained in a mass of 30 lb of smouldering sawdust or 60 lb of brickwork, or 120 lb of steel at a temperature of 800°F. Thus if an area of 25 ft^2 of brickwork has been heated to a depth of $\frac{1}{4}$ in to a temperature of 800°F that brickwork will contain sufficient heat to vaporise a dangerous quantity of alcohol; contact with a flame at 1,800°F for 2 to 3 minutes could supply this heat to the brickwork.

The rate at which spilled spirit would vaporise on a hot surface will depend on the heat transfer rate to the spirit. This is unlikely to exceed the maximum rate of heat transfer which occurs when a fluid boils on a surface; this is about 60 to 80 Btu/ft^2s. Shortly after spillage occurs the heat transfer will drop since thermal resistance of the solid itself becomes the main controlling factor. Thus if spirit were to flow over brickwork 1 in thick heated to 800°F to a depth of 1 in the heat transfer would be expected to drop to 4 to 5 Btu/ft^2s in about 2 minutes and the amount of heat transferred in that time would be about 400 Btu/ft^2. It thus follows that contact of an area of about 25 ft^2 of brick or concrete surface with flame for about 5 minutes will heat the material sufficiently to allow a subsequent leak of spirit of about 2 gallons onto the surface to produce a dangerous pocket of flammable vapour in about 1 minute. The above times would be reduced to about $^1/5$th if the material were metal.

4. Flammable atmospheres may be produced within casks and tanks, heated in a fire. The explosion of such atmospheres would almost certainly cause a loud report and wreck the container. However, it would not be expected to cause any damage to the building unless the ratio of the volume of the tank to the volume of a building was greater than 1 to 200. For a 300,000 ft^3 compartment there may be danger to the building in an explosion of a tank greater than about 10,000 gals capacity.

5. If the oxygen concentration of the atmosphere in a compartment is reduced by a combustion process to less than about 12-14 per cent then flaming combustion would no longer take place. However, the atmosphere may still be very warm and smouldering combustion would also be able to continue. This could result in the vaporisation of a substantial quantity of alcohol vapour. Under these conditions the atmosphere can become rich such that when air is introduced by a door or window being opened either deliberately or as a result of the fire, the concentration of flammable vapour in a pocket may be diluted to a value between the flammable limits. If an ignition source is also present as for example smouldering combustion bursting into flame, then an explosion may follow. This type of explosion is that which may occur when firemen enter smoke logged buildings. If the number of windows or the available ventilation area present is small it is possible that flames will become established at the vent and not in the building. As a result the rate of flow of alcohol vapour from inside the building may die down leading to a reduction or extinction of flame at the vent. This can lead to a further entry of air through the vent leading to the formation of a vapour air pocket inside the building through which flame can propagate later with some violence which could lead to the breakage of further windows or even building collapse and also to the expulsion of vapour and flame at the vents. This type of periodic combustion has been observed to take place in a 3 ft model size scale with fibreboard fuel and with an area of ventilation space equal to about $^1/60$ to $^1/6$ of the area of one side. The flames ejected from the vent usually lasted 2 - 3 seconds. It is possible that this type of burning took place in the Queensferry fire and may have taken place at other fires where the ventilation area was not plentiful.

Pressure development by rapid spread of fire

It has been shown that if fire were to burn at a very high rate in a confined space then a substantial pressure rise may occur as the atmosphere of the building is heated (6). The order of rate of burning which can produce a pressure rise which can be dangerous is about 0.25 lb/ft^2 s of available opening. Thus if a cask were to form a spray leak due to pressure inside the cask and the spray ignited, or if there were a leak over a large area which was ignited immediately, then a pressure of 2 - 3 lb/in^2 may result within a few seconds due to the high burning rate. The rate of rise of pressure, however, under such conditions is small compared with explosions due to the inflammation of the correct mixtures of air and vapour. The sudden breakage of casks and dispersion of the contents into a hot atmosphere may also account for a spread of fire sufficiently rapid to develop a pressure and may also account for periodic intense burning of vapours at nearby windows.